

Heavy quark dynamics in QCD matter

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Abstract. Simultaneous description of heavy quark nuclear suppression factor R_{AA} and the elliptic flow v_2 is a top challenge for all the existing models. We highlight how the temperature dependence of the energy loss/transport coefficients is responsible to address a large part of such a puzzle along with the the full solution of the Boltzmann collision integral for the momentum evolution of heavy quark. We consider four different models to evaluate the temperature dependence of drag coefficients of the heavy quark in the QGP. We have also highlighted the heavy quark dynamics in the presence of an external electromagnetic field which develops a sizable heavy quark directed flow, $v_1(y)$, can be measurable at LHC.

1. Introduction

On going experimental efforts at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies is aimed at to create and characterized the properties of quark gluon plasma (QGP). The heavy mesons (mesons which contain one heavy quark, mainly c and b) constitute a novel probe of the QGP properties, because they are produced in the early stage of the heavy-ion collisions and they are the witness to the entire space-time evolution of the QGP.

The two main experimental observables related to heavy quarks dynamics in QGP are: (i) the nuclear suppression factor, R_{AA} [1, 2] which is the ratio of the p_T spectra of heavy flavored mesons (D and B) produced in nucleus + nucleus collisions to those produced in proton + proton collisions scaled with the number of binary collision and (ii) the elliptic flow, $v_2 = \langle \cos(2\phi_p) \rangle$ [2, 3], which is a measure of the anisotropy in the angular distribution of particle production. Several theoretical efforts have been made to study the R_{AA} and the v_2 measured in experiments within different models [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] (see also for heavy baryons [18]). However all the approaches shown some difficulties to describe both the R_{AA} and v_2 simultaneously.

2. Results

To address the simultaneous description of R_{AA} and v_2 , we need to focus on the time evolution of R_{AA} and v_2 to know how they develop during the expansion of the QGP. As shown in Ref. [19], the R_{AA} develops mostly at the very early stage of the QGP evolution within 3-4 fm/c, while the v_2 builds up later and consequently can be transferred to the heavy quarks also only at later stages when the fireball has reached temperatures close to the critical temperature. This indicates a more liquid-like behavior of the quark-gluon plasma and the T-dependence of the drag coefficient plays a significance role for a simultaneous description of R_{AA} and v_2 as they

are sensitive to the two different stages of the QGP evolution (T_i and T_c). To investigate the influence of the temperature dependence of the drag (and diffusion) coefficients on heavy quark observables, four different models have been used to calculate the drag and diffusion coefficients.

Model-I (pQCD): In this case, the elastic collisions of heavy quarks with the bulk consist of light quarks, anti-quarks and gluons have been considered within the framework of pQCD having temperature dependence of the coupling [20]:

$$g^{-2}(T) = 2\beta_0 \ln\left(\frac{2\pi T}{a T_c}\right) + \frac{\beta_1}{\beta_0} \ln\left[\ln\left(\frac{2\pi T}{a T_c}\right)\right] \quad (1)$$

where $\beta_0 = (11 - 2N_f/3)/16\pi^2$, $\beta_1 = (102 - 38N_f/3)/(16\pi^2)^2$ and $a = 1.3$. N_f is the number of flavor and T_c is the transition temperature.

Model-II (AdS/CFT): In this second case, we consider the drag force from the gauge/string duality i.e. AdS/CFT [24], $\Gamma_{conf} = C \frac{T_{QCD}^2}{M_{HQ}}$, where $C = 2.1 \pm 0.5$ and the diffusions coefficient deduced from fluctuations-dissipation [25].

Model-III (QPM): In this case, we employ a quasi particle model (QPM) [26, 27] with T-dependent quasi-particle masses, $m_q = 1/3g^2T^2$, $m_g = 3/4g^2T^2$, along with a T-dependent background field known as bag constant, tuned to reproduce the thermodynamics of the lattice QCD. The fit lead to the coupling, $g^2(T) = \frac{48\pi^2}{[(11N_c - 2N_f)\ln(\lambda(\frac{T}{T_c} - \frac{T_s}{T_c}))]^2}$, where $\lambda=2.6$ and $T/T_s=0.57$.

Model-IV ($\alpha_{QPM}(T)$, $m_q = m_g = 0$): In this fourth case, we consider a model where the light quarks and gluons are massless but the coupling is taken from the QPM model discussed above. This case is merely a way to obtain a drag increasing toward T_c .

This fourth case has been considered to have drag coefficient with a T dependence similar to the T-matrix approach [5, 28]. In Fig 1, we have shown the variation of the drag coefficients obtained within the four different model discussed above. Our methodology is to reproduce the same R_{AA} as of the experiments within all the four models, hence, these are the rescaled drag coefficients.

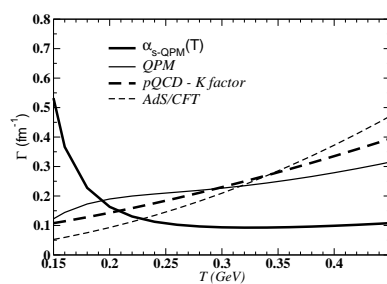


Figure 1. Drag coefficients as a function of T at $p=100$ MeV.

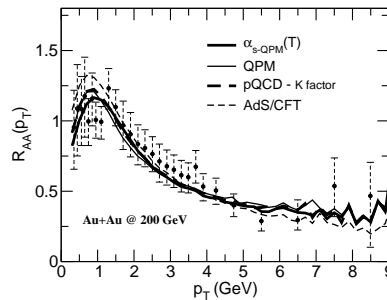


Figure 2. R_{AA} as a function of p_T for the minimum bias.

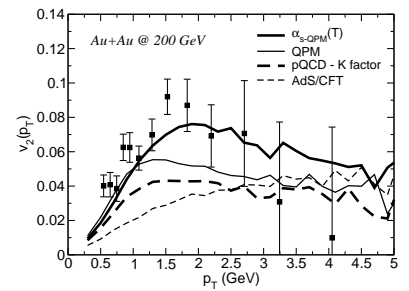


Figure 3. v_2 as a function of p_T for the minimum bias.

We have solved the Langevin dynamics to study the heavy quark momentum evolution in QGP starting from charm quark production in p-p collision [23] as the initial charm quark distributions in the momentum space. To simulate the heavy quark dynamics in QGP, we need the bulk evolution. We are using the transport bulk which can reproduce the gross features of the bulk i.e the spectra and elliptic flow. For the $Au + Au$ collisions at the highest RHIC energy, we simulate the QGP evolution with initial temperature in the center of the fireball is $T_i = 340$

MeV and the initial time is $\tau_i = 0.6$ fm/c. For the detail of the fireball evolution, we refer to our early works [21, 22].

In Fig 2, we have shown the variation of R_{AA} as a function of p_T for the four different models at RHIC energy. The v_2 for the same R_{AA} has been plotted in Fig 3 for all the four models. It has been observed that for the same R_{AA} , the v_2 build-up can be quite different depending on the T-dependence of the drag coefficients. Larger the drag coefficient at T_c larger is the v_2 [9]. Similar effect has also been observed in the light quark sector [29, 30]. This implies, the correct temperature dependence of the drag coefficient has a vital role for a simultaneous description of heavy quark R_{AA} and v_2 . The heavy quark observables are also sensitive to the hadronic rescattering [19, 32], pre-equilibrium phase [33] as well as to the time evolution equation i.e where within Langevin or Boltzmann equation [12]. In particular, the solution of the full two-body collision integral shows that the anisotropic flows are larger respect to those predicted by a Langevin dynamics. For details we refer to our earlier works [12].

In the recent past it has been recognized that a very strong magnetic field [34, 35, 36] is created at early times in high energy heavy ion collisions. Since heavy quarks are produced at the very early stage of evolution due to their large mass their dynamics can be affected by such a strong magnetic field [38, 39]. The \vec{B} field generated in non-central heavy ion collisions dominated by the component along the \vec{y} axis, so its main effect is the induction of a current in the xz plane. On the other hand the time dependence of \vec{B} generates a electric field by Faraday's law, $\vec{\nabla} \cdot \vec{E} = \partial \vec{B} / \partial t$ which induces a current. For the calculation of the electromagnetic field generated in ultra-relativistic heavy-ion collision, we refer to the space-time solution developed in Ref. [37]. In Fig.4 we show the time dependence of the B_y and electric field E_x at finite space rapidity $\eta = 1.5$ in a $Pb+Pb$ at $\sqrt{s} = 2.76$ ATeV at $b = 9.5$ fm for a medium of $\sigma_{el} = 0.023$ fm $^{-1}$. The impact of the electromagnetic field has been taken into account through the Lorentz force as the external force in the Langevin equation. For the detail we refer to Ref. [40].

Magnetic field introduce a anisotropy which eventually leads to a substantial directed flow, $v_1 = \langle p_x / p_T \rangle$, can be measurable at the experiments. In Fig. 5 we have presented the resulting directed flow v_1 as a function of rapidity for charm (black solid line) and anti-charm quarks (dashed line line). We find a substantial v_1 at finite rapidity with a peak at $y \simeq 1.75$. The directed flow is negative for negative charged particle (charm) at forward rapidity which means that the the magnetic field dominates over the displacement induced by the Faraday current (generated due to the time dependence of the magnetic field). This is a non trivial result and depends not only on the absolute magnitude of the magnetic field but also on the strength of heavy-light quark interaction. If we artificially increase the drag coefficient by a factor 5 to achieve a thermalization of the charm quarks similar to the light quark one, this will lead to a quite smaller $v_1(y)$.

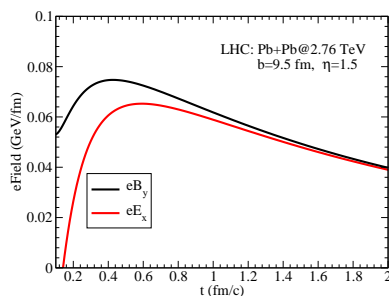


Figure 4. Time evolution in the forward rapidity region of the magnetic field eB_y and the electric field eE_x .

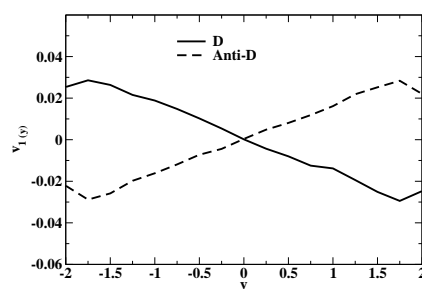


Figure 5. Directed flow v_1 as a function of the rapidity in $Pb+Pb$ at $\sqrt{s} = 2.76$ ATeV for D meson $[c\bar{q}]$ and anti-D meson $[\bar{c}q]$.

3. Summary and outlook

In summary, we have presented how the v_2 build-up for the same R_{AA} depends on the T-dependence of the interaction (drag and diffusion coefficients) which is the key for a simultaneous description of heavy quark R_{AA} and v_2 . We have also mentioned how the v_2 gets a boost from the Boltzmann dynamics by studying the heavy quark momentum evolution and from the hadronic rescattering. We have also studied the heavy quark dynamics in the presence of electromagnetic field. Heavy quark develops a sizable directed flow (v_1) which could be measurable at experiments. The present study suggests the heavy quark v_1 can be considered as a significant probe to characterize the magnetic field.

Acknowledgements

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